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THE APPLICABILITY OF REMOTE SENSING  
TO  
EARTH BIOLOGICAL PROBLEMS

PART II

THE POTENTIAL OF REMOTE SENSING  
IN  
PEST MANAGEMENT

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FINAL REPORT

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## FOREWORD

This report is the second of several planned to deal with the applicability of remote sensing to the management of insect pests that threaten world food and fiber production and human health. This volume is organized similarly to Part I (Polhemus, 1979) of this series, and is in part an addendum to Part I.

Three of the four insect groups treated in Part I have been considered further in this study along with two additional groups.

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## I. INTRODUCTION

This study is a continuation of work begun under a previous NASA contract (NAS9-15598), reported in Part I of this series.

The fundamental purpose of the entire block of study is to establish a scientific basis for assessing the applicability of remote sensing to earth biological problems. The first year of study was restricted to four insect pests that pose a threat to world food and fiber production. In Part I, I summarized the biology, economics and control methods for four diverse insect pest groups and related these to the potential of remote sensing as an aid in pest management. In this report I summarize additional information gathered on three previously studied groups (tsetse flies, desert locusts and western rangeland grasshoppers) and treat two additional groups (Gulf Coastal mosquitoes and range caterpillars) using the same format as in Part I. This report can stand alone, however, if combined with Part I, forms a basic reference for managers and line personnel involved in pest management, data management and remote sensing systems.

Remote sensing methods seem clearly applicable to the pest management of tsetse flies, desert locusts, western rangeland grasshoppers, cabbage loopers and mosquitoes. The means and methods vary greatly from group to group, however, and no simple formula is evident for application of remote sensing to these problems. How present day technology could be applied to the pest management of range caterpillars is not clear given our present knowledge of their biology and ecology.

Trial remote sensing projects in conjunction with ongoing pest management programs are to be encouraged; an excellent example is the desert

locust work being done by the U.N. Food and Agriculture Organization. An overview of the latter is given in this report. Much more field work and correlation with active pest management programs would help greatly in establishing the details of integrating remote sensing into pest management programs. Knipling (1978), while not addressing remote sensing directly, has urged that pest management scientists recognize the potential of advances in technology. Remote sensing should be of particular value in integrated pest control (IPC) both in developed and developing nations (see Brader 1979 for a review of IPC in the developing world).

My recommendations are that NASA pursue development of the multi-spectral resource sampler (MRS) as described by Schnetzler and Thompson (1979). The MRS has 15 m resolution and a pushbroom scanner with pointing capability, both important to a number of applications. A further recommendation is that the remote sensing technology for soil moisture determination be pursued diligently. Lastly, I recommend that continuing consultation be provided to pest management programs worldwide.

Many people have assisted in this study, and to all I am grateful. My special thanks go to: E. L. Maxwell, Colorado State University, Fort Collins, Colorado; C. M. Barnes, NASA/JSC, Houston, Texas; J. Howard, H. Mussman, J. G. LeRoux, FAO, Rome; D.A.T. Baldry, J. N. Pollock, Yves Taze, A. B. Von Ochssee, FAO, Lusaka; M. Lounis, G. Nyborg, FAO Algiers; A. Louis, UNICEF, Algiers; J. A. Onsager, J. Henry, USDA-SER-AR, Bozeman; L. C. Keenan, USDA, APHIS, Lakewood, Colorado; Dan Nees, Colorado Department of Agriculture, Palisades, Colorado; H. C. Chapman, J. Petersen, USDA, Gulf Coast Mosquito Research Laboratory, Lake Charles; J. Olson, J. Welch, Texas A&M University, College Station; Matt Yates, Chambers Co. Mosquito Control District, Anahuac, Texas.

Jelle Hielkema (FAO, Rome) went far beyond any of my expectations in being a gracious host and making sure that I understood the remote sensing activities of the FAO, and I am very grateful. The contract technical monitor, D. S. Nachtwey, has been constructively critical of the work and very supportive; I deeply appreciate his counsel and his help.

## II. SELECTED INSECT PEST GROUPS

Five troublesome insect pest groups were chosen for study. These represent a broad spectrum of life cycles, ecological indicators, pest management strategies and remote sensing requirements. Background data, as appropriate, and field study results for each of these subjects will be discussed below for each insect group.

### MOSQUITOES

Mosquitoes are one of the most troublesome insect pests worldwide and have played a major role in human civilization. They constitute a serious threat to human and animal health, and adversely affect food production.

This study was restricted to mosquitoes of the Gulf Coast region of the United States, especially the coastal marshlands and nearby rice growing areas. Of the many mosquitoes that occur there, three important species were chosen to exemplify diverse life cycles and ecological associations. Two of the species, Aedes sollicitans (Walker) and Psorophora columbiae (Dyar and Knab) are floodwater mosquitoes, and the other Culex salinarius Coquillett, is a permanent water mosquito.

#### 1. Economic Importance

On a world basis, mosquito born malaria is the number one killer. In the United States encephalitis is the most serious mosquito transmitted disease, affecting both man and animals. Pets are seriously affected by heart worm (Filaria), a nematode transmitted by mosquitoes. Livestock

experience weight loss or even death when mosquitoes such as P. colombiae occur in large numbers.

I have not been able to find a statement of the dollar-value of economic losses attributable to coastal mosquitoes, however, all references to this economic loss concur that it is very large. Further, although malaria has failed to establish itself since the 1950's (Louisiana State University, 1977), there is concern that outbreaks will occur again as they did prior to 1950 (Personal Communication, Jesse Hobbs, Center for Disease Control, Atlanta). The major diseases presently known to be transmitted by mosquitoes in the U. S. Gulf Coastal region are five kinds of encephalitis, dengue, and dog heartworm.

## 2. Life Cycle and Ecology

Mosquitoes belong to the family Culicidae of the order Diptera (true flies). They are long-legged slender insects having beadlike antenna (plumose in the males) and many-veined wings. Many species and genera occur in almost every region of the world; King et al (1960) list 74 species in 11 genera for the southeastern United States. Of these, 14 species in six genera are listed by Louisiana State University (1977) as being troublesome in the Gulf Coast region. Some species (e.g. Toxorhynchites rutilus Coquillett) are actually predacious on other mosquitoes and are thus beneficial.

Disease transmission by mosquitoes occurs when an infected female takes blood; at this time disease causing pathogenic organisms may be placed directly in the blood stream. The females urge to bite is caused by the biological need for blood that is a requirement for egg development.

All mosquitoes have four life stages; egg, larva (wigglers), pupa and adult. The adult is an active flying insect, but the other stages occur in water. Some species lay their eggs on moist soil above the water, but all eggs must be submerged in order to hatch. Larvae of all species have four developmental instars, and the pupa are active. Because other details of the life cycle are different for the three species chosen for treatment here, they will be considered separately below.

Aedes sollicitans (salt marsh mosquito) is an important salt-marsh species and one of the most important pest mosquitoes of the Gulf Coast. It is a known vector of Venezuelan equine encephalitis and suspected vector of eastern equine encephalitis. This species breeds in brackish water areas along the Gulf Coast and at some inland sites, usually brackish areas associated with oil production. The eggs are laid on moist soil in intermediate to fresh marshes where they lay dormant until flooded by high tides or rains. Areas subject to periodic, but not daily, flooding are favored. The eggs require 24 or more hours of drying (conditioning) before flooding in order to hatch. After hatching, the aquatic stages require seven to ten days for development depending on water temperature. Along the Gulf Coast breeding takes place throughout most of the year, interrupted only briefly during cold weather. The adults are strong fliers; large swarms migrate from the breeding site in search of host animals, flying commonly 8 to 16 km and up to 64 km from their origin. Migration is at night, however during the daytime they will leave their resting places in vegetation to attack any animal that disturbs them.

Within an undisturbed salt marsh, perhaps 10% of the area produces 99% of the population of Ae. sollicitans (Dr. James Petersen, Personal Communication). The favored areas are poorly drained low spots characterized by

sparse vegetation, mainly grasses, intermixed with bare soil. Disturbed areas, such as dredge spoil areas, seem to be the highest producers of Ae. sollicitans because the area is often much larger than the small breeding areas in undisturbed marsh.

Psorophora columbiae (dark rice field mosquito) is the most important species of the genus in the United States. It occurs in great numbers in the rice land ecosystem. The females are fierce biters, attacking any time during day or night. In large numbers they can kill livestock and make life unbearable for humans outdoors. In addition, this species is the most important vector of Venezuelan equine encephalitis.

The larvae of P. columbiae breed in temporary rain pools, seepage pools, and irrigation and flood waters. Eggs are deposited on moist soil that is subject to flooding. Moist soil with low rank vegetation is ideal, so drained rice fields, fallow rice fields and pastures are favored egg laying sites. If flooded soon after deposition, eggs hatch in four or five days. If they remain in the soil for two or three weeks before flooding, hatching may begin in ten minutes. The larval period in midsummer is as little as four days, and the pupal stage required another one to two days so it is possible to have many generations per year depending on suitable hatching conditions. Adults live one to two months and overwintering is in the egg stage.

Culex salinarius is extremely abundant along the Gulf Coast, and regularly constitutes the vast majority of all adult mosquitoes identified in mosquito control programs in this area. The females bite readily out of doors and occasionally enter dwellings. Along the coast breeding occurs mostly in brackish and fresh intermediate marshes, however, inland they breed almost anywhere in fresh or foul water in ponds, pools or even bilge

water in boats. This is one of the most severe pest mosquitoes in the Gulf Coast region, and is a known vector of Saint Louis encephalitis.

### 3. Dispersal

Dispersal in mosquitoes is by adult flight. The flight range is quite variable, depending on species, but in general suitable habitats within 16 km of an original breeding site are readily colonized. Aedes sollicitans has a flight range of up to 64 km. Because of the potential for a large number of generations per year and a high dispersal capability, any habitat suitable for a given species is likely to be colonized.

### 4. Control Strategy

Early control measures included oil coating of waters and use of insecticides. The use of DDT during and after World War II was very effective in reducing mosquito populations, but is now banned because of its severe deleterious environmental effects. Presently, chemical abatement (larviciding and adulticiding) plus physical control or source reduction measures are the major methods of control. Preventative control has been effective when project planning included provisions for minimizing mosquito problems. Integrated pest management of mosquitoes has been implemented only in trials but is seen as important in the future.

Chemical control of mosquitoes continues to play a major role in most mosquito control programs. This technique yields immediate reduction of populations and may be the only practical present means to avert or terminate massive populations as well as epidemics of mosquito-transmitted diseases.

There are strict pesticide laws in most areas, however, that prevent their wholesale use as seen in the 1950's. Restricting the use of insecticides is sensible for a number of reasons, but the most pressing ones are the prevention of massive environmental damage and the propensity of insects to develop insecticide resistance over time.

Biological controls, an alternative to chemical controls, should ideally fit into the same mosquito control framework existing today which rather restricts the number of candidate organisms. Pesticide companies are unlikely to foster the development of biological controls because they are relatively unprofitable; this coupled with minimal funding for research and development of biologicals has caused progress in this area to be very slow. The attributes of chemical and biological controls from the viewpoints of those responsible for their development are shown in Table 1. Classes of biological control agents, excluding genetic manipulations, are invertebrate predators, vertebrate predators, parasites and pathogens. Unfortunately only a handful of organisms from all of these classes potentially can meet the criteria of a good biological as given in Table 1. Chapman (1974) has given an excellent review.

Genetic manipulations, including the sterile male technique, deserve mention as a promising alternative to chemical control. In an integrated pest management trial at Lake Apastepeque, El Salvador, the sterile male technique was used in conjunction with releases of a biological, the nematode Romanomermis culicivorax.

##### 5. Post Management Requirements

A survey of suitable habitats is necessary to determine actual population levels and species composition. Because of their importance to human health,

**Table 1. Comparison of Desirable Attributes of Chemical and Biological Mosquito Control Agents**

<b>Chemical (Pesticide)</b> <b>(From the viewpoint of the Pesticide Marketing Industry)</b>	<b>Biological</b> <b>(From the viewpoint of the Biological Control Scientist)</b>
<ol style="list-style-type: none"> <li>1. Moderate product cost.</li> <li>2. Good profit.</li> <li>3. Wide target spectrum.</li> <li>4. Wide environmental application.</li> <li>5. No recycling in the field.</li> <li>6. Patentable.</li> <li>7. Technology intensive.</li> </ol>	<ol style="list-style-type: none"> <li>1. Kills the host.</li> <li>2. Narrow target spectrum (Host specific).</li> <li>3. No environmental competition.</li> <li>4. Easily disseminated by standard pesticide application techniques.</li> <li>5. Inundative heavy dose will kill 100% immediately.</li> <li>6. Low dosage will get broad coverage.</li> <li>7. Extensive recycling in the field.</li> <li>8. Easily mass produced (not manpower intensive).</li> </ol>

mosquito biology is well understood compared to most other insect groups, and the literature is enormous. The most important requirement in management of mosquito populations is identification of actual or potential sources and the most effective management tool is source reduction. In particular, monitoring spoil area changes, subsidence, and salinity are of critical importance in the Gulf Coast area.

Efforts have been made or are now underway to correlate remotely sensed data with extensive scientific ground truth data for at least two of the species (Ae. sollicitans, P. colombiae) chosen as candidates here. For the first candidate species, the work is being done by the Gulf Coast Mosquito Research Laboratory, Lake Charles, Louisiana (contact: H. C. Chapman) and for the second by the Entomology Department, Texas A&M University, College Station, Texas (contact: Jim Olson, John Welch). Both projects are in the Gulf Coast region. Unfortunately, neither project has sufficient definitive correlative data assembled so far to warrant presentation here. The consensus, however, is that the following kinds of data are needed for mosquito management of the three candidate species: 1) Ground sampling, 2) temperature, 3) hourly rainfall data (did it rain?), 4) tide maps, 5) soil moisture, 6) vegetative community maps. Ground sampling has been discussed previously; temperature must be plotted vs. species because the maturation rates differ; tide maps can use automatic recorders at chosen localities, but the required accuracy is not yet known; soil moisture is considered probably useful, and while the exact utility is not yet known, it would certainly be useful to know which areas stay wet; vegetative communities are clearly tied to preferred breeding sites but vary greatly in extent and species association.

Of the kinds of needed data enumerated above, those that can be potentially provided by remote sensing are 2, 3 or a part thereof, 5 (probably) and 6. The remote sensing requirements for these data are given in Table 2.

Table 2. Remote Sensing Requirements for Pest Management

Insect Group	Parameter	Remote Sensing Requirements				Candidate Systems	Applicable Existing Systems?
		Temporal Coverage	Spatial Resolution	Band(s)	All-Weather Capability	Pointing Capability	
Mosquitoes	Detailed Habitat - Mapping (incl. vegetative communities)	Weekly	5-15 m.	Multispectral-Visible & IR	No	Yes	No
	Temperature	Daily	1 km	Thermal IR	Yes (In Part)	No	Yes
	Rainfall	Hourly	1 km	Visible & thermal IR	No	No	Yes
	Soil Moisture	Daily	1 km	1) 4.75 GHz Microwave 2) 0.4-1.6 GHz Microwave	Yes	No	No
					Yes	No	Yes

## 6. Field Study

Field studies in the Gulf Coast area around Anahuac, Texas, and Lake Charles, Louisiana, provided first hand observations of the breeding sites of the three mosquito species treated in this work. Fortunately, I was able to accompany experts in mosquito control to various sites, e.g., Matt Yates, Chambers County Mosquito Control District, Anahuac, Texas, and Dr. H. C. Chapman and staff members, Gulf Coast Mosquito Research Laboratory, Lake Charles, Louisiana. Visits were made to spoils areas, rice lands, and undisturbed marsh. The group at Texas A&M (under Jim Olson) has gathered IR imagery of all types of mosquito habitats in this area, so my usual practice of gathering paired IR and color photographs was not followed for mosquitoes.

### RANGE CATERPILLAR

The range caterpillar is a pest that destroys range grasses in ten counties of New Mexico and a small adjacent area in southeastern Colorado and the Oklahoma and Texas panhandles. In spite of the rather restricted range of this pest, it is considered serious because of the extensive range damage that occurs during outbreaks. The literature concerning these insects is relatively small; the review work of Watts and Everett (1976) list only 11 references directly dealing with range caterpillars or their parasites.

The reasons for outbreaks and for the spotty distribution within the range are poorly understood. For this reason the primary emphasis of this study was on field work to determine how remote sensing could help in working out the biology of this pest. Only a small part of the total study effort involved the range caterpillar.

## 1. Economic Importance

The range caterpillar (Hemileuca oliviae Cockerell) infests more than 5 million acres in northeastern New Mexico and, to a limited extent, the adjacent States. This pest has been reported periodically since the late 1800's. Outbreaks of this insect are cyclic and the present one began in the early 1960's. Approximately 600,000 acres of the 5 million acres infested are considered to have a serious economic infestation.

Evidence gathered to date indicates that the range caterpillar eats nothing but grass. In high concentrations the larvae completely denude the rangeland, developing a pattern of "windrowing" wherein great hordes of fifth and sixth instar larvae occur as a result of movement from denuded areas in search of food.

The range caterpillar feeds on range grasses down to, but not including, their roots. About 40 different kinds of grasses are included in the list of host plants, however, the grama grasses (Bouteloua species) seem to be the preferred grass. It has also been reported to seriously injure cultivated grains and forage crops, including millet of various kinds, wheat, oats, barley, milo, maize and Sudan grass. The damage to such crops has usually occurred where isolated farms were surrounded by infested range pastures. It is primarily destructive to range land.

The range caterpillar injures the range forage in two ways: (1) The larvae which grow from 1/5 inch to almost four inches in eight to 12 weeks, consumes large amounts of foliage, often down to the crown, (2) grass which is not eaten by the caterpillar is rendered unpalatable to livestock by the irritating spines on the active larvae and on their cast skins, which remain on the grass throughout the remainder of the growing season

and into the winter. When the spines come in contact with the tender portions of the human skin they cause, at first, an intense local irritation or smarting, which later results in a swollen and itching condition similar to that caused by the sting of a wasp. It is suspected the same thing happens to the mouth of livestock grazing upon the grass, and after one experience the plants are left untouched. For this reason many areas of rangeland not actually destroyed by the range caterpillar are rendered unusable for grazing. Cattle also will not graze areas where pupal cases are prevalent.

Most of the forage is consumed during the fourth and fifth stages of the larvae when they disperse in search of food. This period is usually during July and August and corresponds with the rapid summer growth period of blue grama (Bouteloua gracilis), a warm season grass that accounts for the majority of the forage on the Kiowa National Grassland and constitutes a significant part of the available forage in eastern New Mexico.

The average annual production of forage within the proposed control area is approximately 900 pounds (dry weight) per acre. Under proper management, utilization by livestock grazing is about 50 percent. It is reported that an infestation rate of 12 larvae per square yard will consume about 400 pounds of forage per acre. This amounts to 45 percent of the forage in the average production year and is nearly equal to proper utilization standards. Infestations of 18 to 20 larvae per square yard will consume more than the forage available for livestock. The total amount consumed is not known since, as the density of larvae increases, the average amount of forage consumed per each larvae is decreased. However, heavy infestations on rangeland have removed all of the forage produced.

Livestock production is the major industry within the area infested by the range caterpillar. The New Mexico Department of Agriculture estimates that the losses from range caterpillars to the livestock industry during the past decade have been 20 to 30 million dollars.

## 2. Life Cycle and Ecology

The range caterpillar, Hemileuca oliviae cockerell, belongs to the family Saturniidae in the order Lepidoptera, or moths. The life cycle is quite typical of a Lepidopteran, consisting of four stages: egg, larva, pupa, and adult. The eggs are deposited by the female moth as early as September and as late as November, depending upon the season. The eggs may be deposited most anywhere, but mainly on stems of grasses, weeds, yucca, or other vegetation. They are laid in rowed clusters. The winter is passed in the egg stage. The larvae (worms--caterpillars) hatch from the eggs mainly in May or June when (if) suitable climatic conditions prevail--moisture and warm daytime temperatures. Five or six instars (larva/stages) occur. The larvae begin pupation in late August or September in a loose built cocoon on grass or weeds. Adult moths begin emerging from pupal case mainly between the middle of September and the month of October. Flight of the female moth is the principal method of spread. Mating takes place during the adult flight period when eggs are deposited and the life cycle is repeated.

The adult moth of the range caterpillar (Hemileuca oliviae) is a brownish to clay colored insect with a fairly stout body. The abdomen of the male may be brown or reddish; in the female it is always dark brownish. The adult is about 1 to 1-1/2 inches long with a wing span of 2-1/2 to 3 inches.

The late instar larvae have a smooth, dark red to black head with coarse white hairs of intermixed length; mouth parts and antennae are black. The body is usually "ground" color yellow (grayish yellow to sometimes blackish) and densely covered with large, flattened, yellow granules (secondary tubercles) so that the general effect is yellow; body contains spinose tubercles (spines), black in color and usually branched.

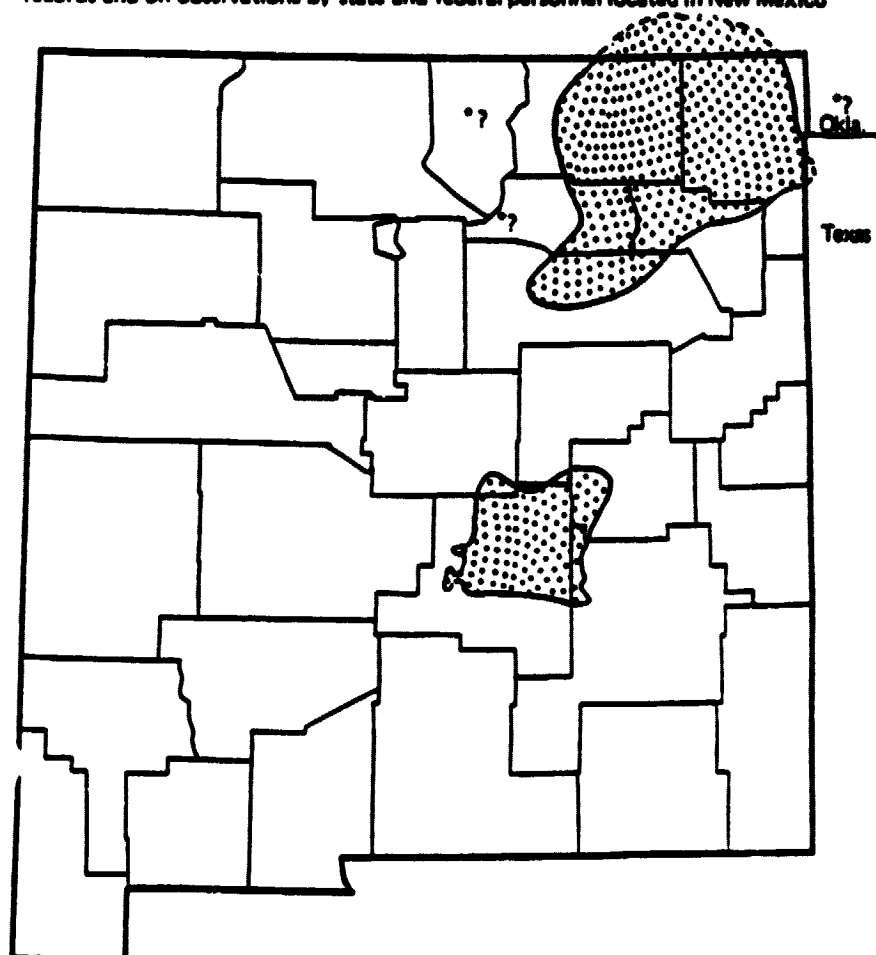
Occurrence of the range caterpillar is characterized by two noteworthy features. First is its distribution, which is relatively limited. Records indicate outbreaks of high significance have occurred only in the northeastern corner and south-central portion of New Mexico. Whether occurrences in other places in New Mexico, Oklahoma, Texas, or Colorado will ever develop into significant outbreaks is unknown, but it has not done so within the period from 1895 to this date.

Secondly, is its pattern of periodic (cyclic) outbreaks which have at times seriously depleted the grass resource on large acreages of range, but always within the same general area of northeastern New Mexico with the exception of the recent outbreak centered in Lincoln County.

The reason for its confinement to the two more or less precisely prescribed areas of occurrence (Fig. 1) is speculative but some features are common between the two. The elevation is similar, ranging from about 5800 to 7800 ft. The terrain is open, rolling grassland with a fairly continuous ground cover. This ground cover characteristic implies a reasonably consistent rainfall pattern during the growing season. The significance of the ground cover relates to the apparent low tolerance of the caterpillars to a high bare ground temperature. Larvae placed on hot, bare ground have been observed to die rather quickly. During extremely hot weather they have been observed to crawl up on fence posts and other perches, presumably to avoid the heat of the ground. Caterpillars have not been observed in wooded terrain and few, if any, in brush country. Instead they are found in the best grazing country. The vegetation in the two areas is similar but at the same time is greatly different from that on much of the territory separating the two areas.

The range caterpillar apparently will feed on any kind of grass, including the agronomic grasses. There have been reports of the caterpillar

Fig. 1. Range caterpillar distribution (shaded area) based on published records and on observations by state and federal personnel located in New Mexico



\*? represents old published records that have not been verified in recent years or that originally may have been in error. (Oklahoma infestation now confirmed.)

(From Watts and Everett, 1976)

feeding on various types of broad leafed vegetation. Apparently what has been observed was caterpillars congregated on other types of vegetation, perhaps to avoid the heat of the ground. There is no evidence of them feeding on anything except grasses.

### 3. Dispersal

Dispersal of range caterpillars is primarily by flight of the adult moths. The apparent poor dispersal capability may be due to the short adult life span, or to ecological factors limiting their distribution. The dispersal potential of the adults is perhaps best understood by examining what is known of their flight patterns and behavior.

Adult emergence begins around the first of October and continues into November or later. Adults have no functional mouth parts and thus take neither food nor water. As might be expected then, they live only a very few days. The moths typically emerge from the pupae during the forenoon, crawl up on the vegetation and remain most of the day while their wings expand and harden. About an hour before sundown the males begin their searching-mating flight, moving from one clump of weeds to another in search of a female. Females take to flight somewhat later than the males and are seen in flight in considerably less numbers than the males. There is no discernable relationship between female flight and mating behavior.

Males are attracted to virgin females but over a fairly short distance and over a very short period of time. This is demonstrated in the searching flight of the male which may fly within inches of many different females before he is attracted to one for mating. Literally hundreds, or even thousands, may be seen in such flight. Then, just at dusk all flight

ceases for a time and with a flashlight one or more pairs can be observed in copula on almost every weed or clump of vegetation. Later, in the early hours of the night, both males and females take to wing in mass and fly mostly in one direction which is generally downwind.

Ranchers living in infested areas are well acquainted with the strong attraction of moths to lights. It is reasonable to say that only males are attracted to light since our observations show that the two sexes are found at light in a ratio of roughly 1500 males to one female. Even among the small numbers of females that have been seen at lights, some were gravid while others were spent.

During the second day of their life the females deposit their eggs and die, some the same day while others may live over into the third day. Males may live as much as four or five days..

#### 4. Control Strategy

Because of the large areas needing treatment and the relatively low value of rangeland early in this century, ranchers historically relied on parasites to control range caterpillars. Wildermuth and Frankenfeld (1933) suggested that the egg parasite Anastatus semiflavus Gahan terminated the outbreak in 1916 but there is no other evidence of substantial biological control. On the other hand, just what conditions are required for the onset or termination of a major outbreak are not well understood, however reduced rainfall and subsequent reduced grass growth may play a significant role.

In modern times rangeland worth has increased dramatically in comparison to insecticide costs, so that insecticides are now the favored control method. Some experiments are ongoing with various parasites to

determine if biological control is feasible but chemical control will most likely be used for some time to come.

The current outbreak of the range caterpillar began to attract attention in 1960 in the vicinity of Abbott in southern Colfax county, New Mexico. The infestation expanded and intensified during the succeeding years and in 1966, some 60 thousand acres were sprayed with a pound of toxaphene per acre in the first chemical control program undertaken for this insect. This was the typical cooperative program in which the cost was split three ways between the rancher, the state and the federal government. In 1967 more than 450,000 acres were sprayed and good control was obtained. The major portion of the heavily infested territory was controlled, so in 1968 there was no widespread damage. However, the previously untreated population produced enough offspring so that in 1969 the infestation was both as extensive and intensive as it had been in 1966 and 1967 but no control program was initiated. By this time most ranchers were thoroughly convinced of the potential destructiveness of this pest and plans got under way early in 1970 to initiate a widespread control program. The environmentalists took a very active interest in these plans and one result was a Federal District Court case. Although the court ruled in favor of the ranchers, no cooperative program with toxaphene could be undertaken because of a difference of opinion among different state and federal agencies regarding the potential hazard of toxaphene to non-target organisms. However, individual ranchers at their own expense, treated in excess of 650,000 acres in 1970. An extensive monitoring program of streams and lakes for the succeeding 12 to 18 months by personnel of the Plant Protection Division completely vindicated toxaphene as a threat to the aquatic environment, the principal point at issue with the environmentalists.

It is unclear whether insecticides will eventually be banned and biological control used to large extent to combat range caterpillars; however, the task of determining the severity and geographical boundaries of outbreaks would seem to remain the same.

### 5. Pest Management Requirements

The primary pest management requirements for range caterpillars have to do with monitoring the extent and severity of outbreaks and environmental conditions that would either work for or against large population densities. There are problems associated with this; one is the propensity of range caterpillars to cluster together and form pockets of very high population density interspersed with low population to uninfested areas within a large infested area. Other problems are that the factors limiting geographical range are not understood, and the overall biology is not well understood.

Temperature and moisture, the latter perhaps expressed in vegetative vigor, are parameters affecting larval hatching times, maturation and possible die-off. I have not listed these in Table 2 because it is not at all evident that the remote sensing of these parameters will be very useful in a pest management program. Larvae that hatched as much as a month apart all began pupation soon after August 15, so with that date as the final for completion of chemical control operations and the ground surveys necessary in any case to determine infested areas, I fail to see where remote sensing is of help in the management phase.

From the research side, however, I think remote sensing can play a key role in cheaply providing parametric data over the substantial area

in which this pest occurs. Indeed, remote sensing may be the only way to effectively survey all of this region at reasonable cost. The key questions that remote sensing can help solve are: 1) What factors limit the boundaries of range caterpillar breeding populations?, 2) what factors affect population densities and in what ways?, 3) what factors affect larval hatching time?

#### **WESTERN RANGELAND GRASSHOPPERS**

Introductory material, economic importance, biology and ecology, control strategy and pest management requirements for western rangeland grasshoppers were presented in Part 1 of this series (Polhemus 1979) and will not be repeated here.

Fortunately, I was able to obtain an in-depth review of Part I during a field trip to Montana and Wyoming. A brief summary is given below, along with the field trip results.

## 1. Review of Part I

Part I was reviewed by the personnel of the USDA Rangeland Insects Laboratory at Bozeman, Montana, and a few corrections and comments are worthy of note:

A) Control programs involving insecticide spraying of rangelands have been estimated at about \$1/acre (in 1977 dollars), whereas it is estimated that the biological control method using Nosema will result in treatment costs of \$110-\$150/km<sup>2</sup> (not including aircraft costs) or about 15 to 40 percent lower than present ultra low volume malathion technology.

B) Dempster (1963) furnished a comprehensive review of the biology and ecology of western rangeland grasshoppers. This was cited extensively in Part I. According to Dr. John Henry and Dr. Jerry Onsager some of Dempster's material is somewhat speculative and should be treated with caution until proven out. The particular statements in question deal with starvation due to non-feeding during cloudy, cool weather, and grasshopper migration. These should be treated as hypotheses.

## 2. Field Work

A field trip to the Sheridan, Wyoming area was completed in July 1979. The purpose of the trip was to determine the potential of remote sensing in control projects using either insecticides or Nosema.

Test plots were visited that were controls, insecticide treated and Nosema treated. These plots were scattered over a rather wide area, with as much as 30 miles between groups of plots. The grasshopper density varied considerably in these plots, but all had considerable hopper populations. Numerous infrared and color photographs were taken of plots with

high populations of hoppers and plots with low populations. There were no evident vegetative parameters common to high population areas but absent from low population areas. This might be expected because of the mosaic vegetation pattern. A previously proposed test area some distance west of Sheridan was abandoned for 1969 tests because excessive rainfall caused grasshoppers to die in that area.

Thus, this field work supports my conclusions given in Part I that the primary use of remote sensing in grasshopper control would be to monitoring air temperature, rainfall and overall vegetative classes and vigor. Some of the methodology worked out by Maxwell et al (1980) for drought monitoring would be applicable to this problem.

#### TSETSE FLIES

In Part I (Polhemus 1979) a rather complete treatment was given for tsetse flies; this material will not be repeated here.

Results of a field trip to Tanzania were also reported in Part I. The emphasis during that trip was on two species, Glossina morsitans Wiedemann and G. pallidipes Austen, particularly with respect to differentiating the habitats of these two species and additionally differentiating these from non-tsetse areas. Because G. morsitans is perhaps the most troublesome tsetse species, and because its preferred habitat is known to shift significantly over its range, a field trip to Zambia was a part of the current contract effort. The purpose was to assess the applicability of remote sensing to tsetse control in a savanna region having West African rather than East African climatic influence, but still concerned with G. morsitans.

## 1. Field Work

Through the kindness of Dr. D. A. T. Baldry (Lusaka) and Dr. J. G. LeRoux (Rome), both of the United Nations Food and Agriculture Organization (FAO), tsetse field data was obtained from the FAO project in Zambia during February 1980. This is a research project to delineate tsetse abundance, seasonal changes and control methods. Training will be provided on a regional basis. The facilities and laboratory are well organized and appear quite adequate. A field camp at Lutale (about 150 km west of Lusaka) was established shortly before my visit and from this base of operations, I was able to do field work adjacent to the Kafue National Park in an area heavily infested with Glossina morsitans.

The savannah of Zambia is very different from that on the Mkwaja Ranch in Tanzania where I did field work previously. Zambia has a West African rather than East African rainfall pattern, the forest is different, and the physiography is greatly different. The forest in the Lutale area is characterized as Munga (Combretum wooded grassland with Papilionaceae on transitional soils) and Miombo (Isoberlinia paniculata-Brachystegia woodlands on sandy plateau soils), with tsetse largely restricted to the latter. The Miombo is intersected extensively by dambos or shallow grassy draws that form the typical water courses of the area. Deeply cut stream courses are rare. Between Lutale and the tsetse area to the west, a 5 km game cleared strip with two game fences form a tsetse barrier. In the Miombo game is abundant but moves seasonally and was scarce in our study area during my visit. According to Baldry, the game moves back from the higher areas during the dry season.

The project people here are interested in temperature mapping and multispectral imaging as potential aids in mapping tsetse distribution and abundance. The NOAA series of satellites would probably provide adequate resolution (1 km) for temperature mapping. The multispectral scanner (MSS) or IR mapping is more problematic. Dr. Baldry intends to obtain Ektachrome IR photography from project helicopters, and I recommend this procedure to evaluate the potential utility and required resolution of MSS data.

I obtained a number of Ektachrome IR photographs of a major project study area, Dambo 57. The most important feature that is immediately evident is the striking contrast between the dambo grasslands and the Miombo, even in the wet season. It is desirable that a seasonal continuum of such imagery be obtained for evaluation of seasonal changes and moisture conditions and correlation of tsetse abundance as determined by surveys with Challier-Laveissiere traps.

In Part I, I suggested that tsetse and non-tsetse areas in the savanna could be delineated by multispectral imagery, based on the different spectral response of grasslands (non-tsetse) and woodlands (potential tsetse area) during the dry season. The contrast between grasslands and woodlands during the wet season in Zambia further supports this idea. Detailed mapping of tsetse habitats will, I believe, require very fine resolution of the sort available with aircraft, some sophisticated processing, and early intensive ground survey. Okiwelu et al (1978) report finding tsetse in supposed non-tsetse areas that had been mapped on the basis of vegetation; I do not yet have the details of how the maps were made but they were prepared by EARTHSAT Corporation so presumably used satellite imagery. With

satellite imagery broad tsetse/non-tsetse areas can be identified, I believe, but until much finer resolution imagery is available from satellites, aircraft surveys will be needed to prepare detailed habitat maps.

Subsequent to the Zambia visit, I briefed a number of people at FAO Headquarters in Rome (gathered together by the director of AGA, Dr. Harry Mussman) on my work so far and discussed with them the possible use of remote sensing in tsetse control. The FAO is considering this technique in conjunction with a tsetse control pilot project in West Africa (Ivory Coast and Senegal) as early as 1981 and would welcome further consultation.

#### DESERT LOCUST

In Part I of this series I presented background material and discussed in some detail the economic importance, life cycle and ecology and control strategy for desert locusts. I touched only briefly on the pest management requirements and the remote sensing work being done by the U. N. Food and Agriculture Organization to support locust control efforts. These will be discussed in more detail here.

The FAO has two cooperative desert locust control programs underway that use remote sensing data, one in the MALT countries (Morocco, Algeria, and Tunisia, with a principal test site in Algeria) and one recently begun in India to replace a cancelled project in Iran. The following is a summary of their approach and rationale, drawn from FAO furnished information.

# 1. FAO Remote Sensing Applications for Desert Locust Survey and Control

Crops worth 15-20 billion dollars over 30 million square kilometres in 60 countries, from Mauritania to India, and Tanzania to Turkey, with a fifth of the world's population, are prone to ravages by the Desert Locust, estimated at \$20 million during a plague period. Over the past 25 years, FAO has developed a scheme of prophylactic control by devising a three-tier system: at national, regional, and inter-regional levels, of surveillance and timely control. In 1977 the recession in Desert Locust activity has entered its sixteenth year, against the previously known longest period of seven years, over 200 years of recorded locust history; an ample measure of success of the scheme. The present locust plague is generally acknowledged to have reached this level due to the lack of effective surveillance.

Effective surveillance of the breeding areas, which extend over the most arduous desert lands of the world, is the key to the success of locust control. The present methods of ground and aerial surveys are limited both in time and space, and can be undertaken in certain areas only in certain seasons. The use of satellite data to detect vegetation and rainfall, and thus the prospective breeding grounds, could possibly confine the search to specific areas in which the survey teams could be sent directly, enhancing the effectiveness of survey and control operations considerably.

An information system based on satellite remote sensing and providing spatial and temporal continuous intelligence on the ecological conditions for desert locust breeding at inter-regional, regional and national scales is intended to aid in preventing future locust upsurges from expanding to plague proportions. This information structure should significantly strengthen the effectiveness of desert locust survey and control

activities during recession periods. Also, systematic monitoring of precipitation and vegetation development over large areas will generate information which is of interest to a range of other fields, e.g., range-land management, hydrology, agrometeorology, food production information-gathering, desertification studies.

In late 1977, following the successful completion of a pilot project investigating the potential of using various remote sensing technology applications for improving current methodology of international Desert Locust Survey and Control, a comprehensive follow-up project for further development and operational application was prepared and submitted for funding. The Southwest Asian Desert Locust Commission Region was chosen as project area and the location of project headquarters was to be Teheran, Iran, in view of the satellite receiving and data processing facilities then being established in Iran.

In 1978 the political situation in Iran changed to such an extent that it culminated in the evacuation of all UN staff in December 1978. In the same time frame, the international Desert Locust situation changed from a 16-year long recession into a major upsurge of Desert Locust activity which is now termed a low-medium level plague. The consequence of these facts is that a reorientation concerning both the location and the structure of the project was required in order to optimize the use of currently available remote sensing techniques for operational and research activities at various levels (i.e., HQ, regional and field levels).

The Pilot Project, undertaken with FAO's Remote Sensing Unit in Algeria and funded by the Regional Locust Trust Funds, has yielded various approaches for the use of remote sensing techniques for desert locust survey and control. Among these are the use of high frequency METEOSAT and GOES-I/O visible and Thermal IR imagery for obtaining rainfall data in the MALT area

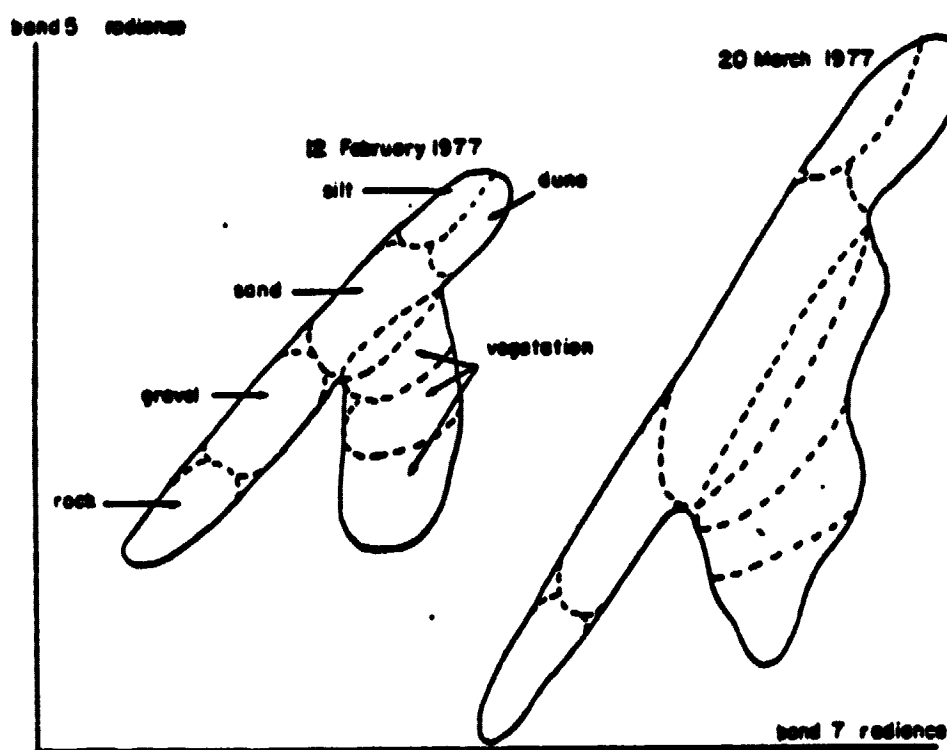
coupled with LANDSAT data for the detection and monitoring of ephemeral vegetation. The program formulated for India calls for the evaluation of TIROS-N/NOAA-6 data for both rainfall mapping and ephemeral vegetation monitoring, along with LANDSAT data for the latter use. In addition to satellite data, available ground truth and synoptic weather station data are used.

## 2. Visit to FAO Headquarters, Rome

Jelle Hielkema spent a great deal of time with me and explained in detail the remote sensing work being done on the desert locust program. He is analyzing mainly LANDSAT imagery whereas the group in Algiers in cooperation with Dr. Barrett (Bristol University, U.K., consultant) are analyzing weather satellite data. Hielkema is using products furnished by the European Space Agency (ESA) facility at Fucino, Italy, and we visited there. He uses color transparencies, character density plots and CRT on-line presentations in his analysis. The latter two are obtained from IBM Rome where the ER-MAN II program has been installed. (ER-MAN II was originally developed for the LACIE program at NASA-JSC, but has been installed on IBM systems at various localities. See Gilmore, 1977.)

We performed on-line interactive processing of some LANDSAT scenes from the Algerian Sahara at the IBM facility. The best results were obtained by level slicing with a ratioed band 5/7 classifier having a translocated zero axis of the line of soils. (See Kauth and Thomas, 1976, and Figure 2.) Classification was done by choosing training sites on a false color CRT presentation of bands 4, 5, and 7. For the particular scene processed,

**Fig. 2.** Band 5/7 feature space of 262144 pixel subscenes of Landsat scene 205/41 of 12/02/1977 and 20/03/1977.



(From Hielkema, 1980)

ground truth was not available. Class statistics were computed and displayed, then a Bayesian classification was completed using a maximum likelihood run and classes were presented at both 80% and 100% classification.

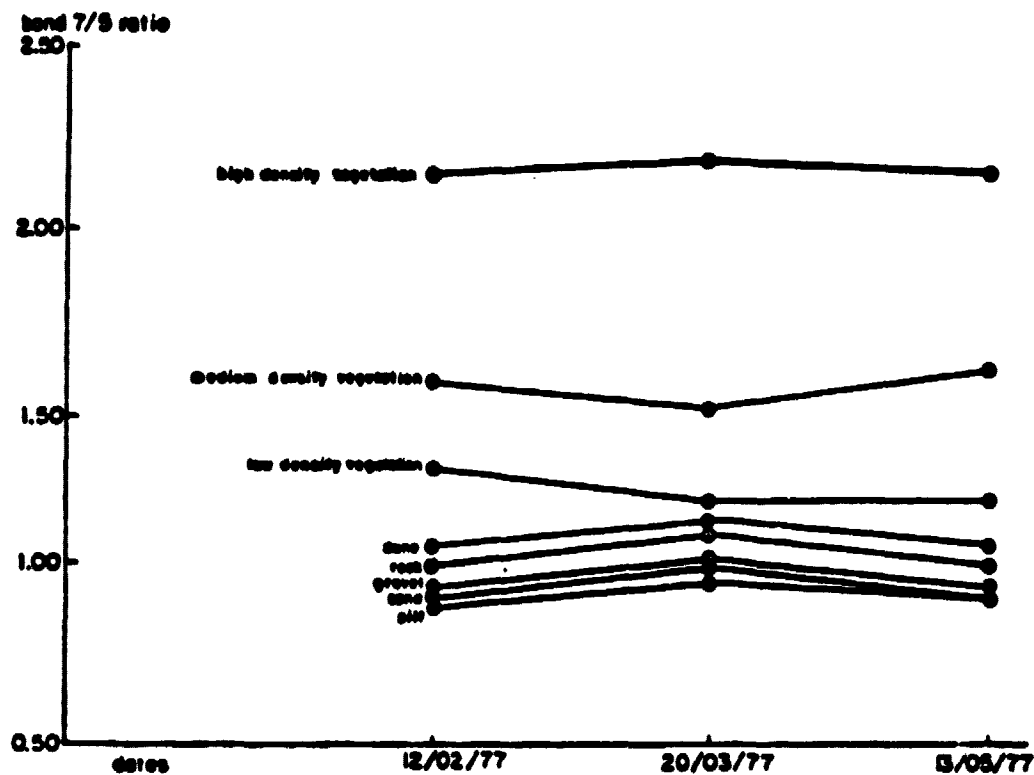
The ratio method for arid land classification follows closely the results obtained independently by Dr. E. L. Maxwell of Colorado State University during a NASA funded drought monitoring project (see Maxwell et al, 1980). The arid land classification work being done in the U.S. and that of the FAO are clearly synergistic and close liaison should be encouraged; however, it appears that the detection and monitoring of ephemeral vegetation in the Sahara, for instance, is a much easier task for remote sensing than classifying vegetative communities in the arid western U.S. Figure 3 shows the response of vegetation and soils in the Sahara.

### 3. Field Work

Field work was accomplished in the Algiers area and in southern Algeria. The FAO has a small remote sensing facility at Algiers where efforts consist largely of archiving NOAA weather satellite pictures awaiting a consultation visit by Dr. Barrett to commence analysis. Mr. Mustapha Lounis kindly showed me through the facilities and we discussed some of the registration and overlay problems.

On a brief trip out of Algiers to the vicinity of Médéa, I obtained a number of paired color and Ektachrome IR photographs that are in marked contrast to those obtained further south in the Sahara. The differences in IR response to the vegetation of semi-arid and arid (Sahara) areas is striking.

**Fig. 3.** Multitemporal fluctuation pattern of corrected spectral class band 7/5 ratio values.



(From Hielkema, 1980)

In southern Algeria I visited a desert locust outbreak area near Tamanrasset. The purpose was to correlate physiography, climate, soil, and vegetation characteristics, and IR imagery of the latter with arid areas of North America. I was successful in doing this because through the kindness of Dr. Andre Louis, I joined a party making a tour of Touareg villages on a UNICEF mission and thus toured a substantial part of the Hoggar including the areas around Irafok and Ideles. I obtained a number of paired color and Ektachrome IR photographs that demonstrate the low vigor of the very sparse vegetation.

The Sahara is much drier and has much less vegetative cover in general than the deserts of North America. The higher areas observed all appear to be massive basaltic formations with unconsolidated materials of drifted sand and eroded basalt. Vegetation is rare in most areas, and sparse even at high altitude. Adventitious greening in the Oueds (washes) would be much more easily discerned with multispectral imagery than in the North American deserts. Even where substantial oases are present (e.g., Ideles) the vegetation is sparse and covers a very small area. To the north, isolated oases (I-n-Salah, Ouargla, El Golea) have extensive areas of palms, but little else except small irrigated patches of wheat. The task for remote sensing associated with identifying potential desert locust outbreak areas appears much simpler than that of predicting rangeland grasshopper problem areas in the western U.S., but some of the methodology of the former can be applied. Tracking the efforts of the FAO remote sensing group is recommended.

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